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ORIGINAL RESEARCH

COVID-19 Quarantine Measures Efficiency Evaluation by Best Tube Interval Data Envelopment Analysis

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Abstract
All countries have responded with a wide range of measures to stop the propagation of coronavirus. We apply best tube interval data envelopment analysis, in order to evaluate efficiency of quarantine measures using imprecise data. Using the Oxford COVID-19 Government Response Tracker's (OxCGRT) data and given method, we construct time series of efficiency assessment of government responses to COVID-19. In addition, we separate all examined countries into several groups with similar patterns of quarantine measures efficiency. As a result, we highlight China and Vietnam as a benchmark for all other countries, because efficiency of these countries is high for almost whole period of research.

Keywords COVID-19 · Data envelopment analysis · Efficiency evaluation · Quarantine measures · Law-abidingness · Interval data

1 Introduction

COVID-19 is the current global pandemic of the COVID-19 coronavirus infection, caused by the SARS-CoV-2 coronavirus [1]. In March 2020, the World Health Organization declared the COVID-19 coronavirus outbreak a pandemic. To contain the spread of the unexplored virus, unprecedented measures have been taken: countries of the world have closed borders, stopped air and sea passenger traffic, and have been forced to introduce total lockdowns — close shops, bars, restaurants, museums, theaters, leisure places, stop transport, transfer employees to remote work, and seriously restrict movement in cities.

However, different strategies of restrictions introduction cause different consequences. In addition, some local factors can influence on the infection rate.

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For instance, it is well known that the quarantine in Sweden was much more polite than in other countries. This approach has its own advantages and disadvantages. Economic losses caused by shutdown of the business in the country were very low. On the other side, it was claimed that for a certain period of 2020, Sweden had the highest mortality rate in Europe [2].

In turn, China actively responded to a threat and promptly implemented very strict quarantine measures. Severe punishment, up to the death penalty, was threatened for those who were convicted of manufacturing and distributing counterfeit medicines, maliciously infecting other people with the coronavirus and causing serious harm to doctors during the coronavirus outbreak. It afforded the chance to stop further spread of the coronavirus (by the 15th of June 2021, China has about 105,000 infected and less than 5000 deaths [3]). However, it caused serious economic losses — China's economy shrank by 6.8% in the first quarter of 2020 [4].

In this paper, we propose to use data envelopment analysis (DEA) in order to evaluate the efficiency of the quarantine measures implemented in different countries.

2 Model Description

DEA is a well-known and widely used approach for the efficiency evaluation of the similar objects [5–7]. It was proposed by Cooper, Cooper, and Rhodes in 1978 based on Farrell's idea [8] that the efficiency of the object e_k can be analyzed as the ratio of weighted sums of output (y_{ik}) and input (x_{jk}) parameters of the decision making unit (DMU)

$$e_k = \frac{\sum_{i=1}^{M} u_i y_{ik}}{\sum_{j=1}^{N} v_j x_{jk}},$$

where M and N represent the number of output and input parameters and u_i and v_j are nonnegative weight coefficients showing the factor importance. For the choice of weight coefficients, Cooper et al. proposed to use an optimization model, which maximizes the efficiency of the chosen object from the sample [9].

Herewith, it was proposed to keep the efficiency of the DMU inside interval $[0, 1]$ for the interpretability of the model results (efficiency of the object should lie between 0 and 100%). Parameter weights are non-negative; feature values are usually also positive (or transformed into positive on the data preprocessing step). So the efficiency assessment will be larger than 0. Therefore, it is necessary to add only one constraint

$$\forall k \frac{\sum_{i=1}^{M} u_i y_{ik}}{\sum_{j=1}^{N} v_j x_{jk}} \leq 1$$

Thus, we get the following optimization model

$$\max_{u_i,v_j}\left(e_k = \frac{\sum_{i=1}^{M} u_i y_{ik}}{\sum_{j=1}^{N} v_j x_{jk}}\right)$$

such that

$$\begin{cases} \frac{\sum_{i=1}^{M} u_i y_{il}}{\sum_{j=1}^{N} v_j x_{jl}} \le 1 l \in \{1,\dots,L\} \\ u_i \ge 0 i \in \{1,\dots,M\} \\ v_j \ge 0 j \in \{1,\dots,N\} \end{cases}$$

where L is the number of the objects in the sample.

As a result of weights optimization, we obtain the efficiency evaluation for the certain object, compared with all other objects in the sample. Afterwards, a similar optimization problem for each DMU is solved.

However, this methodology requires precise data. Meanwhile, statistics considering COVID-19 infections and deaths caused by coronavirus is not so accurate because of several factors, such as not total testing of population, storing, and aggregation of data from different regions.

Therefore, we propose to use interval modification of DEA — best tube interval data envelopment analysis (best tube IDEA) [10]. According to this modification, we transform values of the parameters into parameter intervals by adding and subtracting certain percent of the value (pair $\left(y_{ik}^{-}, y_{ik}^{+}\right)$ instead of y_{ik}). This percent depends on our data confidence (it is a parameter of the methodology, chosen by the user).

After data preprocessing we construct 100% efficiency frontier by basic DEA using the centers of parameter intervals. Nonetheless, best efficiency evaluation (100%) is assigned not only to the object on the frontier, but also to the object incomparable with them (if both inequalities $y_{ik}^{+} > y_{il}^{-}$ and $y_{il}^{+} > y_{ik}^{-}$ hold, intervals $\left(y_{ik}^{-}, y_{ik}^{+}\right)$ and $\left(y_{il}^{-}, y_{il}^{+}\right)$ are overlapping, and objects k and l are called incomparable with each other). Moreover, objects with best variant (highest outputs and lowest inputs inside parameter intervals) higher than efficiency frontier get 100% efficiency as well.

For instance, in Fig. 1, we have an example of best tube IDEA application to the generated dataset. All objects (bold dots and stars) are surrounded by rectangles showing parameter intervals. In this dataset, we got three completely efficient DMUs (stars). Object A gets 100% efficiency because it lies on the efficiency frontier. Object A’ is incomparable with A, so it also will be efficient. And object F has its own version (top left corner of the rectangle), which is higher than 100% frontier, so it also gets 100% efficiency assessment. All other DMUs are below the so-called best tube and get their efficiency evaluation by basic DEA.

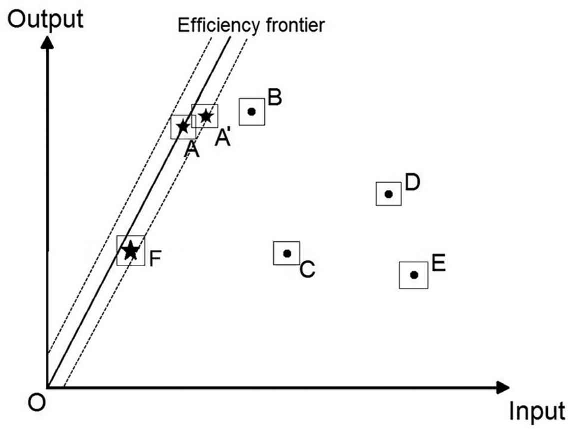

Fig. 1 Example of best tube IDEA application

3 Data Description

We obtained the data from the Oxford COVID-19 Government Response Tracker (hereafter OxCGRT). OxCGRT systematically collects information on several different common types of restrictions, which governments have made in response to the pandemic, and has data from more than 170 countries.

The data about indicators are ordinal and have different numbers of grades for different quarantine measures. The number of grades for each criterion is presented in Table 1.

Besides, OxCGRT also collects time series data about the number of infected patients, which allows to evaluate quantitative results of quarantine measures in different countries.

In addition, it is important to point out that the same government instructions might be implemented differently in different countries. For instance, in some law-obedient countries, such as China or Germany, wherein case of enterprises closing and government recommendations not to leave home the majority of residents will stay at home and work remotely. In contrast, in some other countries

Table 1 The number of grades for the criteria of quarantine measures [11]

Criterion	Number of grades
Closure of enterprises	4
School closure	4
Canceling of public events	3
Restrictions on international travel	5
Restrictions on internal travel	3
Restrictions on exit from home	4
Suspension of public transportation	3
Restrictions on meetings and gatherings	5

like Russia or Italy, people will arrange an additional vacation or parties with their friends.

In this regard, we include law-abidingness as one of the parameters. We tried to use different data sources, such as Edelman Trust Barometer [12], or papers studying issues of trust in various countries [13]. However, some sources cover only a small set of developed countries, such as the USA and China, and do not have data for many European countries. Some other datasets have too many missing values. Therefore, we decided to use the expert law-abidingness assessment from the National Research University Higher School of Economics (law-abidingness data is presented in the Appendix 1, Table 2).

4 The Efficiency of Quarantine Measures

For the application of best tube IDEA, we should choose input and output parameters. Taking into account that the implementation of quarantine measures is expensive, we use the degree of implementation of different quarantine measures as input parameters. In addition, we include in the list of input parameters law-abidingness, which influences the efficiency of quarantine measures' implementation.

As output parameters, we decided to use the number of new infected patients. However, it would be incorrect to compare 100 new infected patients for countries with populations of 3 million and 300 million. Therefore, we use the number of new cases over the population of the country, instead of just the number of new cases. Moreover, increasing the number of infected people from 100 to 200 and from 10,100 to 10,200 is not equal in terms of the efficiency of quarantine measures. Hence, we include the ratio of new cases over the total number of infected people as one more output parameter.

In addition, it is important to highlight that quarantine measures' influence on the number of new cases is not immediate. Therefore, for the efficiency assessment, we used quarantine measures for a certain date and the number of new cases in 2 weeks after this date.

In order to throw away all outliers, we apply filters on the data. At first, we did not consider all countries with population less than 10 million. It was done for elimination of small countries for which the number of new infected equal to 100 might be equal to 1% of population. As a result, we got 40 countries.

Moreover, it is important to mention the period of analyzed time period. Firstly, we did not use data from January and February 2020, because propagation of the coronavirus was milder in the beginning of 2020. Secondly, we want to analyze exactly the strategies to halt the spread of coronavirus. Therefore, the time interval was limited to 1 year (until March 2021).

After data preprocessing, we applied best tube IDEA for the efficiency assessment of quarantine measures every 2 weeks. For this purpose, the following optimization problem was solved on the first step for each country (k is the country index):

$$\max_{u_i, v_j} \left(\frac{\sum_{i=1}^{2} u_i y_{ik}}{\sum_{j=1}^{9} v_j x_{jk}} \right)$$

such that

$$\begin{cases} \frac{\sum_{i=1}^{2} u_i y_{il}}{\sum_{j=1}^{9} v_j x_{jl}} \leq 1 l \in \{1, \dots, 40\} \\ u_i \geq 0 i \in \{1, 2\} \\ v_j \geq 0 j \in \{1, \dots, 9\} \end{cases}$$

where y_{1k} and y_{2k} are values of output parameters for k-th country and x_{jk} is input parameters for k-th country (strictness of different quarantine measures and law-abidingness).

Afterwards, we examined all countries which do not obtain 100% efficiency highlighting objects which are in comparable with the best efficiency frontier. For this purpose, we generated "best version" of each country using highest value from output parameter intervals and lowest values from input parameter intervals. Afterwards, we solved the following optimization problem:

$$\max_{u_i, v_j} \left(\frac{\sum_{i=1}^{2} u_i y_{ik}^{best}}{\sum_{j=1}^{9} v_j x_{jk}^{best}} \right)$$

such that

$$\begin{cases} \frac{\sum_{i=1}^{2} u_i y_{il}}{\sum_{j=1}^{9} v_j x_{jl}} \leq 1 l \in \{1, \dots, 40\} \\ u_i \geq 0 i \in \{1, 2\} \\ v_j \geq 0 j \in \{1, \dots, 9\} \end{cases}$$

If "best version" of the country gets 100% efficiency, while on the first step country had lower value of efficiency, we claim it incomparable with efficiency frontier and give it 100% efficiency. All other countries from the sample obtain quarantine measures efficiency evaluation according to the classic DEA model.

For calculation of countries' quarantine measures efficiency, we implemented aforementioned procedure by our own using free and open-source Python library SciPy.

As a result, we obtained time series of efficiency evaluations for all studied countries (24 values in each time series), which allows us to analyze the main trends in quarantine measures efficiency.

Using these time series, we divided all countries into 5 main groups based on the number and features (length, height) of coronavirus waves [14, 15]. Full group division is given in the Appendix 2.

The first group consists of countries which were far from main centers of COVID-19 propagation: Angola, Nepal, and Syria. First infections in these countries appeared as late as in March. However, after that, quarantine measures were

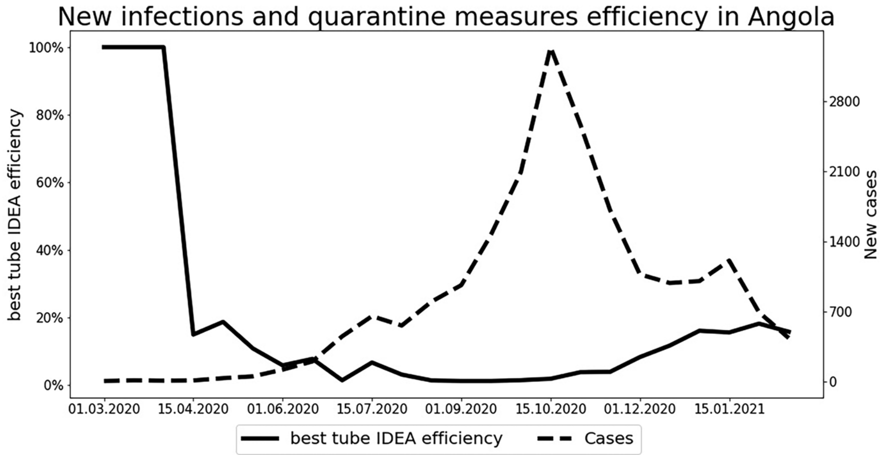

Fig. 2 Quarantine measures' efficiency according to IDEA and absolute increase of new infected cases in Angola (law-abidingness 5 out of 10)

not well organized. As a result, these countries had high efficiency according to best tube IDEA at the beginning of spring 2020 (March, April) and low efficiency for the rest of time (Fig. 2).

The second group consists of just two countries — Vietnam and China. China was the starting point for COVID-19 [16]. There were certain issues with the infections number; however, the government implemented strict quarantine measures. Consequently, propagation of the coronavirus has been stopped sufficiently fast — starting from March, there have been registered less than 1500 new cases for 2 weeks. As a result, the efficiency of quarantine measures is high for almost

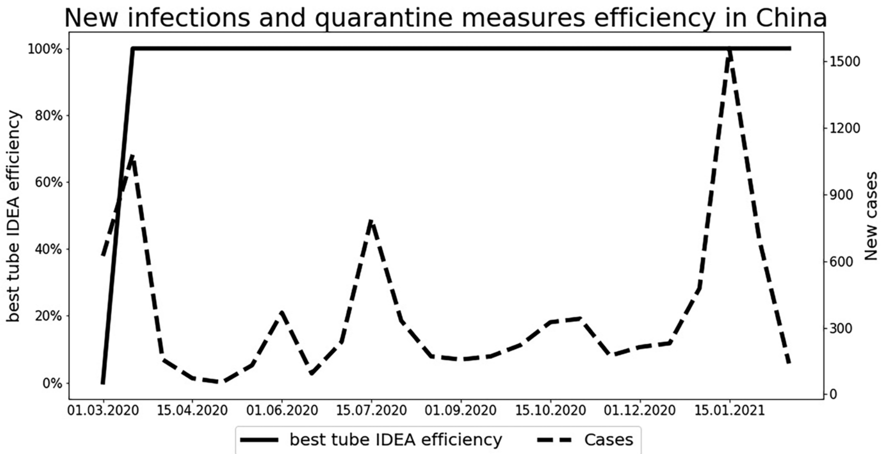

Fig. 3 Quarantine measures' efficiency according to IDEA and absolute increase of new infected cases in China (law-abidingness 10 out of 10)

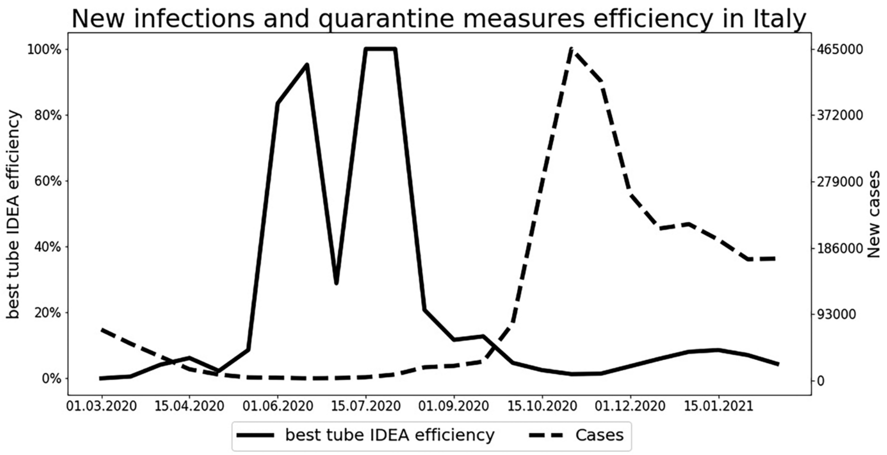

Fig. 4 Quarantine measures' efficiency according to IDEA and absolute increase of new infected cases in Italy (law-abidingness 5 out of 10)

the whole period of time in research. So, China and Vietnam (especially the former one) might be used as a benchmark for all other countries (Fig. 3).

The next group mainly consists of large European countries, such as Italy, Germany, France, and the UK. These countries have strong economic, political, and touristic connection between each other. As a result, their infection rates have certain correlation. At the beginning of 2020, all these countries saw noticeable growth of the new infected cases number, followed by a smooth decrease. However, at the end of summer and beginning of autumn, a new significant step of

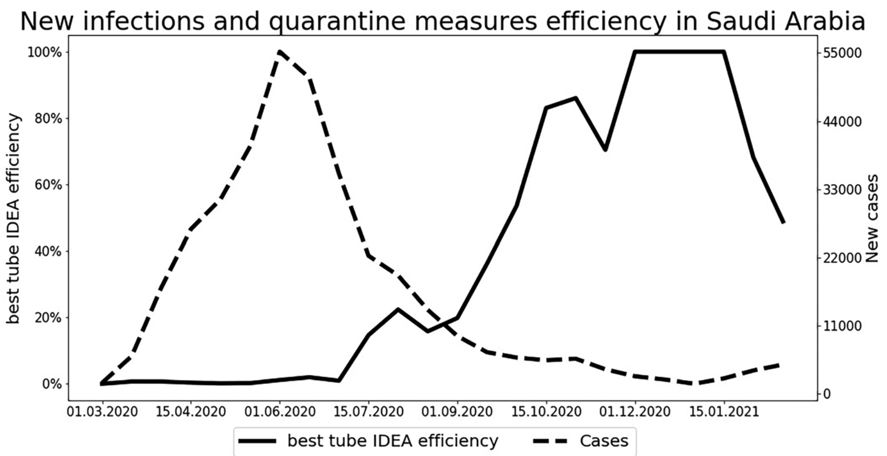

Fig. 5 Quarantine measures' efficiency according to IDEA and absolute increase of new infected cases in Saudi Arabia (law-abidingness 8 out of 10)

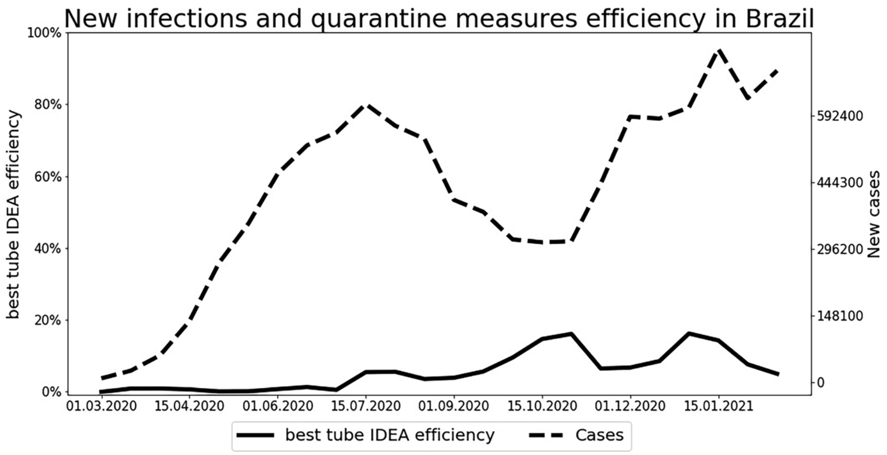

Fig. 6 Quarantine measures' efficiency according to IDEA and absolute increase of new infected cases in Brazil (law-abidingness 6 out of 10)

growth in infected numbers, which is also called "the second coronavirus wave," appeared. Fortunately, in December infection rate went down, but it was still high — a little bit less than 200,000 each 2 weeks. Quarantine measures efficiency increased in late spring of 2020, remained high enough until August, and finally dropped down in September of 2020 at the beginning of second wave of COVID-19 (Fig. 4).

The fourth group, in turn, consists of countries which did not face with aforementioned "the second coronavirus wave": Australia, Azerbaijan, Uzbekistan, and Saudi Arabia. Infection rate in all of these countries decreases from the beginning of the summer 2020, when there was the top of the first wave of COVID-19. And now the number of new infected cases is about 5000 every 2 weeks. Quarantine measures' efficiency, on the contrary, has a positive trend (Fig. 5).

The fifth group represents the rest of the countries. The majority of them have positive (increasing) trend in the new infected case number. Meanwhile, the efficiency of quarantine measures according to the best tube IDEA is usually constantly at a low level — less than 15–20% (Fig. 6).

5 Conclusion

The best tube IDEA allowed us to divide all the countries into five main groups using the dynamics of their quarantine measures: efficiency assessment. This division is interpretable and sufficiently explicit. Hence, we can claim that best tube modification of basic DEA methodology can be practically applied.

In addition, using obtained division, we can give strong recommendation for all the countries to consider Chinese and Vietnamese examples as a benchmark for their own strategies of quarantine measures.

One more important finding of this work is the distribution of countries into several groups in terms of similar behavior of the efficiency curve of imposed restrictions. If group formation of almost all European countries was predictable, it was surprising to find out that the USA are in the same group with Mexico, Algeria, and Brazil (countries with low effectiveness of quarantine measures throughout the whole period in research). However, additional look through the statistical data confirmed this distribution, because the time period from the beginning of 2020 till February 2021 was studied, and noticeable successes in prevention of further spreading of coronavirus in the USA appeared only in the spring of 2021.

Appendix 1: Data on Law-Abidance

All expert assessments are between 0 (complete absence of law-abidingness) and 10 (full law-abidingness).

Appendix 2: Countries Division Into 5 Groups

Group 1 (countries with delayed start of COVID-19 pandemic): Angola, Nepal, Nigeria and Syria.

Group 2 (benchmark countries with high quarantine measures efficiency for the whole period in research): China and Vietnam.

Group 3 (countries with “the second coronavirus wave”): Belgium, Canada, Egypt, France, Germany, Italy, Japan, Kazakhstan, the Netherlands, Poland, Russia, South Africa, South Korea, Spain, Sri Lanka, Sweden, Turkey, Ukraine, and UK.

Group 4 (countries with only one wave of COVID-19 pandemic): Australia, Azerbaijan, Uzbekistan, and Saudi Arabia.

Group 5 (countries with low efficiency for the whole period): Algeria, Argentina, Brazil, Chile, Czech Republic, Greece, India, Iran, Mexico, Romania, and USA.

Table 2 Experts' assessment of law-abidingness in different studied countries

Country	Law-abidingness
Algeria	5
Angola	5
Argentina	6
Australia	7
Azerbaijan	9
Belgium	8
Brazil	5
Canada	8
Chile	6
China	10
Czech Republic	7
Egypt	5
France	6
Germany	9
Greece	4
India	7
Iran	9
Italy	5
Japan	9
Kazakhstan	3
Mexico	6
Nepal	9
Netherlands	9
Nigeria	7
Poland	6
Romania	4
Russia	3
Saudi Arabia	8
South Africa	4
South Korea	8
Spain	4
Sri Lanka	6
Sweden	9
Syria	4
Turkey	6
Ukraine	4
UK	5
USA	4
Uzbekistan	3
Vietnam	7

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Data Availability The authors declare that the data supporting the findings of this study are available within the article.

Code Availability The computer code will be available upon reasonable request to the corresponding author.

Declarations

Conflict of Interest The author declares no competing interests. This work is an output of a research project implemented as part of the Basic Research Program at the National Research University Higher School of Economics (HSE University).

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